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RESPONSE BIASES WITH VIRTUAL IMAGING DISPLAYS

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ABSTRACT

The head-up display (HUD) was developed to provide the pilot simultaneous viewing of flight information and the outside environment. The HUD optics were collimated so that the symbols appear at optical infinity as does the distant terrain. Operationally, about 30 percent of pilots experience an increased tendency toward spatial disorientation when using a HUD. Two experiments were conducted at NADC to determine whether HUD symbols do in fact allow the eyes to focus at optical infinity. And, if not, what is the direction and amount of refocusing necessary to see both the real world and HUD symbols clearly? Results showed that the HUD produces undesirable inward focusing shifts when it is used. When simultaneously using the HUD and viewing distant real-world targets, eye focus is not the same as focus to the real-world targets alone. Also, when using the HUD in clouds, focus is not the same as when using the HUD superposed over distant terrain. Collimated HUD symbols were found to be weak visual stimuli that do not draw eye focus much beyond the resting distance, or dark focus. In general, the HUD allows focus to lapse toward the individual's own particular dark focus. Previous research indicates that when focus shifts occur, the apparent size and distance of real-world objects also change. Judgments of the aircraft's position in space can be erroneous. These judgments are critical in tasks such as terrain following, target bombing, and final landing approach. Because individual differences in focusing are large, redesigning the HUD to incorporate manual optical adjustments may be desirable. Using manual adjustment, the optics can be optimized for each pilot. Pilot accommodation training is another consideration. Further experiments are needed to determine the best redesign and training solutions.

INTRODUCTION

The intention of head-up display (HUD) designers is to provide a means whereby pilots can focus on the real world and simultaneously on displayed symbology. This has been the intention ever since the early days of head-up display development in the 1950s at the United Kingdom's Royal Aircraft Establishment. Designers used the technique of optical collimation of virtual images projected onto a combining glass mounted above the aircraft's instrument panel. The assumption was that the eyes focus at optical infinity when viewing collimated images. Not until the late 1970s was evidence found suggesting that collimated images are not focused at optical infinity by the eyes (Randle, Roscoe, and Petitt, 1980; Hull, Gill, and Roscoe, 1982).

Since HUDs have been used operationally in aircraft, several problems have surfaced. About 30 percent of pilots report that using a HUD tends to cause disorientation, especially when flying in and out of clouds (Barnette, 1976; Newman, 1980). McNaughton (1985) reports disorientation and misorientation* problems when using a HUD and suggests that these problems may be involved in controlled flight into the ground accidents. Pilots have also reported a tendency to focus at the near distance of the HUD combining glass instead of on the outside real-world scene (Jarvi, 1981; Norton, 1981). The resulting HUD myopia appears to be a special case of the more general phenomenon known as instrument myopia (Hennessy, 1975).

Whatever the cause, many pilots find it necessary to reaccommodate when shifting attention between HUD symbology and the outside world. For example, F-14 pilots have said that air-to-air targets are difficult to see when they are inside, or within two degrees of, the HUD-displayed Sidewinder diamond. Conversely, some pilots flying low level have said that they never saw the large 'X' that appears on the HUD as a pull-up cue. The objective of the research presented in this report is to determine the nature and extent of the refocusing problem.

BACKGROUND

The tendency of eye accommodation to remain at or return to its resting position is opposed by the acuity demand of a visual task (Simonelli, 1979). The degree of positive or negative accommodation in or out from an individual's neutral position is determined by the spatial frequencies that must be resolved to perform the task and by the extent, orientation, retinal locus, and spatial frequencies of visible textural gradients surrounding task-related objects. As either a foveal target or surrounding texture is obscured by reduced illumination, reduced contrast from haze or other atmospheric attenuation, severely reduced field of view, or optical defocusing, stimulus adequacy is degraded, and focus lapses toward neutrality (Benel, 1979).

Intermediate Resting Focus

The notion that the resting focus of the eyes might not be at optical infinity was advanced explicitly by several investigators in the 1930s (for examples, see Cogan, 1937). During the 1940s and 50s even more experimenters reported resting or "dark focus" accommodation values at an "intermediate" distance, usually at about arm's length (see Simonelli, 1979, for an excellent review). But it was not until the 1970s with the invention of infrared

* Misorientation occurs when the pilot thinks his aircraft is in one attitude situation but the aircraft is actually in another. That is, the pilot is unaware of any problem. Disorientation implies that the pilot is aware that he does not know his aircraft's attitude.

tracking optometers (Cornsweet and Crane, 1970), laser optometers (Hennessy and Leibowitz, 1970, 1972), and polarized vernier optometers (Simonelli, 1979, 1980) that the dark focus was systematically studied (for reviews see Benel, 1979; Owens, 1976; Roscoe, 1984, 1985; and Simonelli, 1979).

During the 1980s the intermediate distance "hypothesis," as it was cautiously referred to during the 70s by Herschel Leibowitz and his students at Pennsylvania State University, is gradually being recognized as a fact by the scientific community. Its involvements in the "anomalous" empty-field, night, and instrument myopias and in the curious Mandelbaum (1960) effect are now supported by a solid experimental base (Benel, 1979; Hennessy, 1975; Leibowitz and Owens, 1975, 1978; Owens, 1979). Its involvement in the many violations of the size-distance invariance hypothesis, including the "moon illusion" and the "projection" of afterimages, is less well understood and accepted, though repeatedly supported by experimental evidence (Roscoe, 1984, 1985).

Accommodation and Spatial Orientation

The discovery of a relationship between accommodation and apparent size runs directly counter to conventional belief. Other things being constant, the apparent size of an object is proportional to the distance to which the eyes are focused. The correlation between the apparent size of the moon, for example, and focal distance (not apparent distance) is virtually perfect, within the small errors of repeated measurement (Benel, 1979; Hull, Gill, and Roscoe, 1982; Iavecchia, Iavecchia, and Roscoe, 1983; Simonelli and Roscoe, 1979). Also in contradiction to the size-distance invariance hypothesis: with no objective change in a visual scene, the larger an object appears with changes in focal distance, the <u>nearer</u> it seems to be (Roscoe, 1984).

So where a particular eye focuses, within its accommodative range, depends jointly on the acuity demand of the task and the locus and character of visible texture, mainly in the lower half of the visual field and within the spatial frequency range of 0.5 to 14 cycles per degree (Owens, 1979; Benel, 1979). And, where the eye focuses affects not only image clarity and visual acuity but also apparent size and distance and, as a direct consequence, the angular displacement from the line-of-sight of individual objects and surfaces such as an airport runway or a desert terrain. It is now evident that flying mishaps, such as landing short or long and controlled flight into the terrain, frequently are directly attributable to nonveridical spatial judgments associated with misaccommodation.

Virtual Imaging Displays

The problems just described have been exacerbated by the use of collimated virtual imaging displays in aircraft and flight simulators. For many pilots these displays prevent the eyes from focusing at the real or simulated distances of outside objects (Hull, Gill, and Roscoe, 1982; Randle, Roscoe, and Petitt, 1980). Evidently collimation releases the eyes to lapse toward the dark focus, and the bold symbology of typical head-up displays does not require sharp focusing for legibility. Thus, collimation does not cause the eyes to focus at optical infinity as the advocates of head-up and helmet-mounted displays assert, and the consequences are the inability of most pilots to attend concurrently to the collimated symbology and distant objects without

conscious focus shifting and associated losses in distant acuity and veridical spatial orientation.

Optometric Variability

The problem is complicated by several factors, the most notable being the great variability in individual focusing responses particularly in terms of the far point and dark focus. Individuals with far points of 0.5 and -2.0 diopters, respectively, may have comparable near acuity and contrast sensitivity, but there will be a vast difference in their visual performances in reading highway signs, spotting ground targets from the air, picking up bogies, and other tasks for which a distant far point offers a big advantage. In contrast, for near work such as scope reading, an individual's performance will be maximized when the viewing distance equals his or her dark focus (Johnson, 1976), thereby not requiring accommodative effort either in or out to maintain image clarity.

EXPERIMENTAL APPROACH

In view of the growing concern over the problems pilots are experiencing with collimated displays and the evident implication of eye focusing difficulties, two experiments were designed to quantify the effects of viewing and responding to collimated HUD symbology on eye accommodation and real-world visual performance. The experiments were designed to answer the following questions:

- How is eye focus affected when using a HUD?
- What is the extent of refocusing that must occur to respond properly to both the outside world and the display symbology?
- Is the effect different for individuals with different dark foci?

Two experiments were conducted outdoors in daylight. Two rooftops at the Naval Air Development Center, separated by a distance of 182 m, were used. On rooftop number one were the subject and experimenter, a HUD, its associated electronics, an optometer to measure accommodation distance, and a microprocessor to control timing and data collection. The microprocessor was linked to a parallel-to-serial encoder that transmitted equipment-control commands to the remote rooftop via electrical cable. On the remote rooftop was mounted what we refer to as the "scoreboard." The scoreboard is a pentagonal carousel, each face of which is capable of displaying digits of a different size. Descriptions of the experimental equipment follow.

EXPERIMENTAL EQUIPMENT

Head-Up Display

A HUD built by Marconi Avionics for the A-4M light attack aircraft was used. The HUD receives driving signals from a microprocessor and projects the computer-generated symbology into the subject's forward field-of-view superposed on the outside world. The symbol color is the green produced by a P-1 phosphor. The experimental targets are stroke-written seven-segment numerals subtending a 1/2-degree vertical visual angle. The ratio of the

character width to height is 3:4, and the stroke width is 1/8 of character height. These dimensions were chosen to represent the typical size of alphanumerics on operational HUDs. The HUD's circular field-of-view subtends 20 degrees from the viewing eye position. This position is 50 cm from the forward setting of the combining glass. The HUD was carefully tested to ensure proper collimation of projected imagery.

Simulated Clouds

Clouds were simulated through use of a sheet of linen cloth mounted on a Styrafoam frame for stability and placed in the immediate field-of-view of the HUD. The material is such that light can pass through but shapes can not. When in use, the clouds were positioned at a standard viewing distance of one meter from the subject's eyes.

Scoreboard

Distant real-world targets were provided by what we colloquially refer to as "the scoreboard." The scoreboard was a large pentagonal wooden box painted flat black and mounted as a carousel on a rooftop 182 m from the primary experimental station. On each of its five faces (not counting the top and bottom) could be displayed seven-segment numerals of a given size. The scoreboard box was rotated to allow presentation of numerals of the sizes called for in the various experimental conditions.

The segmented numerals were constructed from strips of green Plexiglas filter material independently transilluminated with incandescent bulbs. By remotely switching the various segments on and off, numerals from 0 to 9 could be formed by the computer. Viewed from a distance of 182 m, the resulting appearance of the numerals matched that of the stroke-written HUD symbols in color, shape, and stroke ratio. Luminance of the scoreboard numerals of each size was approximately 2000 fL. With sun shields mounted on the scoreboard to improve numeral visibility in full sunlight, the contrast between illuminated and unilluminated segments was marginally visible.

The vertical visual angles subtended by the scoreboard numerals were 1/8, 1/12, 1/16, 1/20, and 1/24 of a degree. These vertical visual angles were equivalent to Snellen-chart acuities of 20/30, 20/20, 20/15, 20/12, and 20/10. The corresponding heights of the scoreboard numerals were 39.2, 26.2, 19.6, 15.7, and 13.1 cm. With the stroke widths of the characters 1/8 their height to match the HUD, the visual angles subtended by the stroke widths of the respective numerals were approximately 1.0, 0.6, 0.5, 0.4, and 0.3 minutes of arc. All but the largest scoreboard size required resolution greater than the 20/20 line of a Snellen chart.

Polarized Vernier Optometer (PVO)

A PVO was developed under contract by ILLIANA Aviation Sciences Limited. The PVO is a device for measuring visual accommodation, the distance to which the eye is focused. This is done in the following manner. The observer reports whether three optically projected vertical bar segments appear aligned as a continuous vertical bar or whether the central segment appears displaced to the left or right of the upper and lower segments. The bars will appear aligned only when their optical distance corresponds to the distance to which

the eye is focused. This distance, sensed by an optical encoder in the PVO, is then translated by a simple formula into the focal distance of the eye. When the subject reports the bars are aligned, the experimenter has a measure of the momentary static focus of the eye (see Figure 1).

The observer sees the PVO bars reflected from a small combining glass placed immediately in front of one eye. Thus the observer can also perform meaningful visual tasks while looking through the combining glass. When a shutter within the PVO is opened for a brief period, about one-third second, the observer sees the vertical bars superposed on the background scene. The presentation of the bars does not affect the accommodative state of the eye. The "vernier" alignment of the central bar segment relative to the upper and lower segments is easily discerned, and the observer indicates left, center, or right by pressing one of three correspondingly arranged pushbuttons.

In practice, to measure focal state while an observer is performing a visual task, the bar segments are presented several times intermittently over a period of about 20 seconds. After each presentation, the experimenter changes the position of the bars based on the observer's report of the state of their alignment. Initially each change brings the vernier target closer to the position corresponding to the focal distance of the eye. When the approximate position is found, a bracketing procedure is employed, moving back and forth through the momentary focal distance. The change of position on successive presentations is narrowed until the observer reports the bars to be aligned. Several determinations of the position of alignment are made to insure reliability of the measured focal distance.

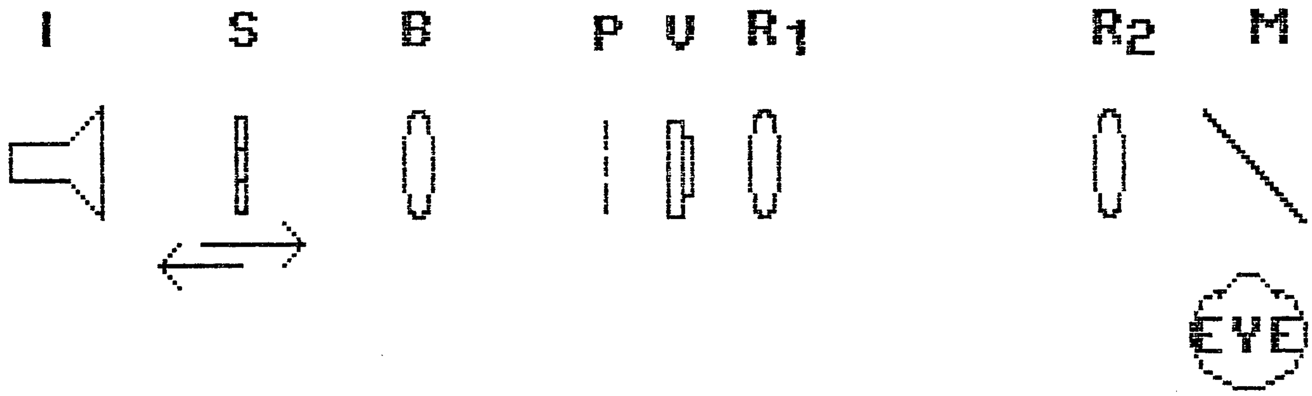
SUBJECTS

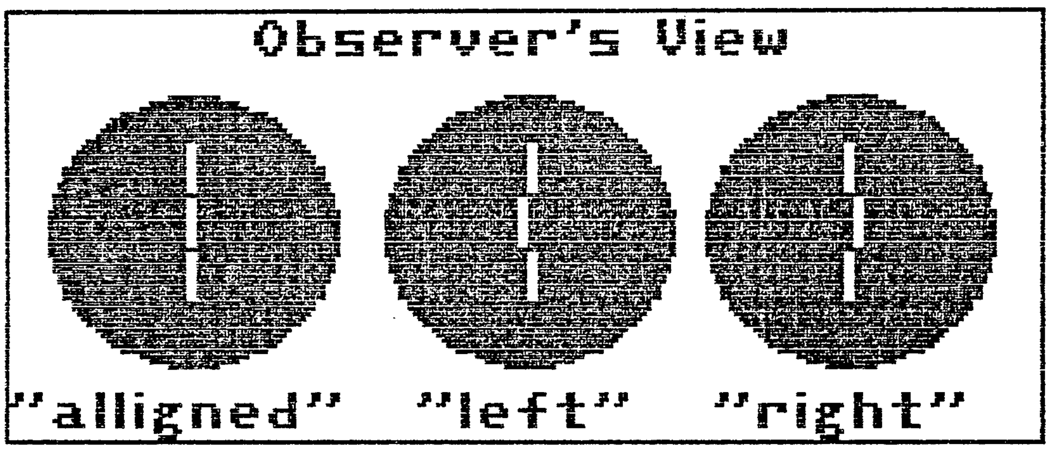
Ten subjects, selected randomly from the enlisted personnel subject pool at NADC, participated in both experiments. All subjects were confirmed by the flight surgeon to have at least 20/20 uncorrected binocular vision and to be free of abnormal phorias. These criteria were chosen because they represent the visual retention requirements for Naval aviators. In addition each subject's near point and far point (accommodative range) were measured.

EXPERIMENT I

Design

Experiment I was a single-factor repeated-measures design. Head-up display background texture was the independent variable with HUD symbology appearing either against a simulated-cloud background or against a distant-terrain background. The presentation order of these two conditions was counterbalanced across subjects. Accommodation was the dependent variable. Control conditions included focus responses to each background while looking through the HUD but with no symbols displayed, focus response to the HUD symbols displayed in darkness, and dark focus or resting accommodation. Controls were measured both before and after an experimental series. The dark focus was also measured at midseries.





I = Illumination source
S = Polarized Slits (moveable)
B = Badal Lens (dbl. convex)
P = Polarized pinholes
V = Shutter
R = Relay lens
M = Beamsplitter

Figure 1. Polarized Vernier Optometer

Procedures

Subjects performed two tasks, an addition task of HUD digits and the optometer-response task. A series of three digits between 0 and 9 were randomly generated by the microprocessor. These digits were sequentially presented in the center of the HUD. The stimulus duration of each digit was 800 milliseconds, and the interstimulus interval was 300 milliseconds. The subject's task was to add the second and third digits and to press one of two right-hand response buttons denoting whether the sum was odd or even. The first digit provided a cue to the location in the HUD where the next two digits would sequentially appear. Subjects were not required to respond rapidly and were instructed that guessing was permitted if they were unsure.

Also, during the last 400 milliseconds of the 800 millisecond duration of the third HUD digit, the optometer bars flashed. The subject was required to push one of three left-hand response buttons to indicate whether the central bar segment was to the left, right, or centered with respect to the upper and lower bar segments. A "did not see" button was also available because the optometer bar flash could easily be missed if the head were slightly out of position.

Thus, for each set of three digits the subject made two responses, a right-hand response to the addition task and a left-hand response to the optometer. The odd/even responses served to ensure that the subjects were in reality looking at the HUD targets. The optometer response was used by the experimenter to readjust the optometer to a new distance and bracket the point at which the subject would see the optometer bars aligned. Following each adjustment, the experimenter initiated the presentation of another set of three digits to obtain another accommodation response. This process continued until the refractive state of the subject's eye to the HUD targets was determined.

EXPERIMENT II

Experiment II was a repeated-measures design with two factors, location of targets (two levels) and target acuity demand (five levels). Targets were located either on the scoreboard only or on both the HUD and scoreboard simultaneously. There were five target sizes on the scoreboard. The presentation order of conditions was counterbalanced across subjects. Control conditions included focus response to the terrain background while looking through the HUD with no targets visible, focus response to the terrain with a HUD digit visible, focus response to a HUD digit displayed in darkness, and the dark focus. Controls were measured before and after an experimental series. The dark focus measure was also repeated at midseries.

RESULTS

In the clouds, collimated HUD symbology does not cause the eyes to focus as they would when distant terrain is visible. In Experiment I the average focus to the HUD used against the simulated cloud background was +0.56 diopter (D). Average focus to the HUD superposed on distant terrain was more distant at +0.10 D (see Table 1). This outward shift on breaking out of the clouds was statistically significant ($\underline{F}(1,9) = 14.71$, $\underline{p} = 0.004$). <u>The HUD does not prepare the pilot to see something outside on breaking out of the clouds.</u>

TABLE 1

Mean Dioptric Measures From Experiment I, Conditions 1, 2, and 3

	Subject										
	1	2	3	4	5	6	7	8	9	10	Mean
1	1.76	1.36	1.34	0.14	1.34	0.16	-0.04	-0.06	-2.22	1.84	0.56
2	1.40	1.02	0.44	-0.38	1.02	-0.06	-0.22	-0.16	-2.54	0.52	0.10
3	-0.36	-0.34	-0.90	-0.52	-0.32	-0.22	-0.18	-0.10	-0.32	-1.32	-0.46

Condition 1 is the HUD against a simulated cloud background.
Condition 2 is the HUD against a distant real-world background.
Condition 3 is the change from Condition 1 to Condition 2.

Actually, focus was at the dark-focus distance when the HUD was used in the cloud. Focus to the cloud background (HUD present but symbology off) and focus to the HUD used in darkness were also at the dark focus. Data are presented in Table 2. The small observed differences among these conditions could easily have occurred by chance ($\underline{F}(3,27) = 1.13$, $\underline{p} = 0.36$). The HUD is a weak visual stimulus that exerts little force to pull the eyes away from their resting point. Just as use of the HUD in clouds does not prepare the pilot to see terrain clearly on breaking out, use of the HUD at night does not prepare the pilot to see something outside like a tanker or wingman with which he must join up.

The difference between focus to the terrain and focus when the HUD is superposed on that terrain was measured in both Experiments I and II. Results are shown in Table 3. As soon as the HUD was turned on and used, a significant inward lapse in focus occurred ($\underline{F}(1,9) = 9.57$, $\underline{p} = 0.013$). In this comparison of HUD-on versus HUD-off situations, the terrain was not involved in any visual task. Under circumstances in which the terrain has no task-related acuity demand, the HUD caused an average inward focus lapse of +0.13 D toward the resting state. When the terrain became part of the visual task, the inward lapse caused by the HUD increased to +0.25 D (Table 4).

Table 4 shows the focus measures obtained in Experiment II. Because focus did not differ for the five target sizes on the scoreboard ($\underline{F},(4,36) = 0.34$, $\underline{p} = 0.85$), the values shown in Table 4 are averages collapsed across all scoreboard size conditions. Focus to the distant scoreboard used alone and focus to the scoreboard and HUD used simultaneously are shown. Notice that the average response of the ten subjects to the scoreboard alone was exactly 0 diopters (optical infinity). The observed difference in focus between using distant real targets alone and simultaneously using HUD collimated targets with distant real targets was highly significant ($\underline{F}(1,9) = 51.41$, $\underline{p} = 0.0001$).

TABLE 2

Mean Dioptric Measures from Experiment I, Conditions 4, 5, 6, and 7

	Subject										
	1	2	3	4	5	6	7	8	9	10	Mean
4	1.67	2.43	0.88	0.28	1.30	0.82	0.77	0.07	-2.58	1.67	0.73
5	1.25	2.00	1.10	0.40	0.55	-0.15	0.83	-0.20	-2.43	1.53	0.49
6	1.78	1.50	1.28	0.03	1.25	0.78	0.73	-0.20	-2.03	1.43	0.66
7	1.76	1.36	1.34	0.14	1.34	0.16	-0.04	-0.06	-2.22	1.84	0.56

Condition 4 is the average of the pre-, mid-, and posttest dark foci.
Condition 5 is the average of the pre- and posttest focus to the HUD in darkness.
Condition 6 is the average of the pre- and posttest focus to the cloud background alone.
Condition 7 is the focus to the HUD used against the cloud background.

TABLE 3

Mean Dioptric Measures of Focus to the Distant Terrain Alone with no Task and Focus when Using the HUD Superposed over the Terrain, Averaged for Experiments I and II, Conditions 8, 9, and 10

	Subject										
	1	2	3	4	5	6	7	8	9	10	Mean
8	1.15	1.09	0.21	-0.49	0.80	0.00	-0.03	-0.32	-2.60	0.43	0.02
9	1.35	1.11	0.47	-0.27	1.11	-0.03	-0.05	-0.17	-2.64	0.69	0.16
10	0.20	0.02	0.26	0.22	0.31	-0.03	-0.02	0.15	-0.04	0.26	0.13

Condition 8 is the distant terrain alone with no task.
Condition 9 is the HUD superposed over the terrain.
Condition 10 is the focus lapse caused by the HUD (9 minus 8).

Focus to the HUD plus real targets is not the same as focus to the real targets alone. In fact, the HUD caused a bigger lapse toward the dark focus when something on the terrain had to be seen and recognized as a target than when the terrain was not important. This comparison of focus to terrain targets alone with focus to HUD-plus-distant-targets is directly relevant to flying. Resolving surface objects is important, particularly in landing approaches, terrain following, and target acquisition/bombing while using a HUD.

TABLE 4

Mean Dioptric Measures from Experiment II, Conditions 11, 12, and 13

	Subject										
	1	2	3	4	5	6	7	8	9	10	Mean
11	0.86	0.96	0.15	-0.48	0.76	0.03	-0.03	-0.01	-1.99	-0.24	0.00
12	1.13	1.10	0.40	-0.27	1.03	0.20	0.26	0.12	-1.75	0.29	0.25
13	0.27	0.14	0.25	0.21	0.27	0.17	0.29	0.13	0.24	0.53	0.25

Condition 11 is the average focus to the distant real-world scoreboard targets only.
Condition 12 is the average focus to simultaneous use of the scoreboard plus the HUD targets.
Condition 13 is the focus lapse caused by turning the HUD on and using it (12 minus 11).

Table 5 shows all of the dark focus measures from both experiments. The differences between Experiments I and II could easily have occurred by chance ($\underline{F}(1,9) = 1.71$, $\underline{p} = 0.22$). However, pre-, mid-, and posttest measures within experiments showed a trend toward a difference ($\underline{F}(2,18) = 2.68$, $\underline{p} = 0.09$). By midtest, the dark focus tended to drift outward. In Experiment I, the dark focus drifted from +0.82 D to +0.68 D. In Experiment II, the drift was from +0.67 D to +0.47 D.

Eye accommodation is controlled by the sympathetic and parasympathetic branches of the autonomic nervous system (Cogan, 1937; Olmsted, 1944; Melton, Purnell, and Brecher, 1955; Benel, 1979). One possible explanation for the outward shift is a sympathetic adrenalin response associated with cerebral activity (Gawron, 1979). However, by posttest, the dark focus drifted back inward, particularly in Experiment II which lasted about 1 1/2 hours for each subject, twice the length of Experiment I. Possibly fatigue toward the end of Experiment II, with an associated parasympathetic response, caused the dark focus to drift back toward its pretest value.

TABLE 5

Dark Focus (DF) Measures Taken During Experiments I and II Showing a Trend of Outward Drift by Midtest and the Subsequent Drift Back Inward by Posttest in Experiment II

	Subject 1	2	3	4	5	6	7	8	9	10	Mean
					Pretest						
I	2.00	2.20	0.85	0.35	1.50	0.50	1.05	0.40	-2.25	1.60	0.82
II	1.15	2.70	1.00	0.55	1.35	0.90	0.65	0.30	-3.20	1.30	0.67
					Midtest						
I	1.60	2.65	0.90	0.00	1.45	0.95	0.50	-0.10	-2.95	1.80	0.68
II	0.75	2.10	0.60	0.30	1.25	1.15	0.40	0.30	-3.40	1.20	0.47
					Posttest						
I	1.40	2.45	0.90	0.50	0.95	1.00	0.75	-0.10	-2.55	1.60	0.69
II	1.30	2.55	0.90	0.20	1.30	0.95	1.30	0.05	-2.80	1.15	0.69
					Average						
I	1.67	2.43	0.88	0.28	1.30	0.82	0.77	0.07	-2.58	1.67	0.73
II	1.07	2.45	0.83	0.35	1.30	1.00	0.78	0.22	-3.13	1.22	0.61

To account for the small variations about each individual's own dark focus measure, data were analyzed with respect to the individual's average dark focus. Scatterplots of the relationship between average dark focus and all other measures are found in Figures 2 and 3 for Experiments I and II, respectively. These scatterplots clearly show that: (1) The dark focus is highly predictive of all other focus measures, and (2) Some people with normal visual acuity never actually focus at optical infinity (0 D). The correlation between average dark focus and all other focus measures was 0.95 for Experiment I and 0.93 for Experiment II. Thus, knowing each individual's dark focus can account for 88% of the variability observed in all the focus measures.

Fortunately, Subject 9, who had normal acuity despite an unusually distant dark focus of -2.86 D, was included in the sample. His data emphasize the point that focusing responses tend to remain within a relatively narrow range about the dark focus, wherever it may be. No matter how demanding the distant acuity task at optical infinity, his focus never came inside -1.75 D. Conversely, subjects with dark foci closer than about 3 m (1/3 D) never focused all the way outward to 0 D. Only two subjects (4 and 8) frequently focused at or slightly beyond optical infinity.

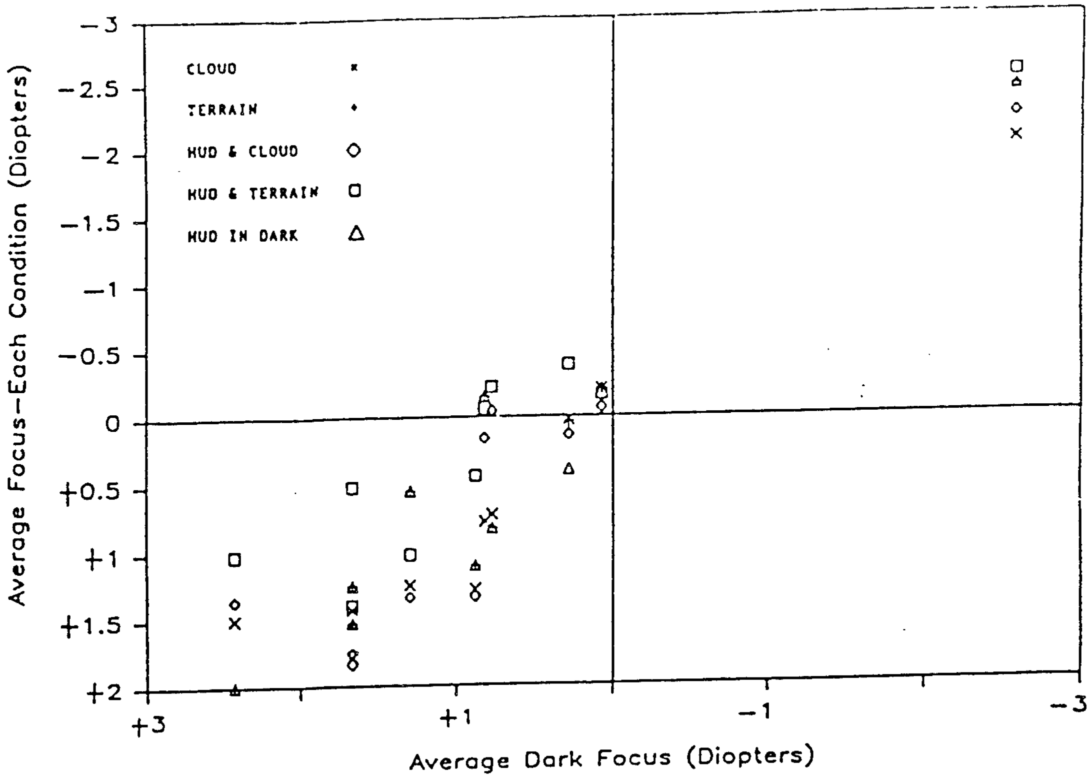


Figure 2. Correlation between average dark focus and all other focus measures taken in Experiment I.

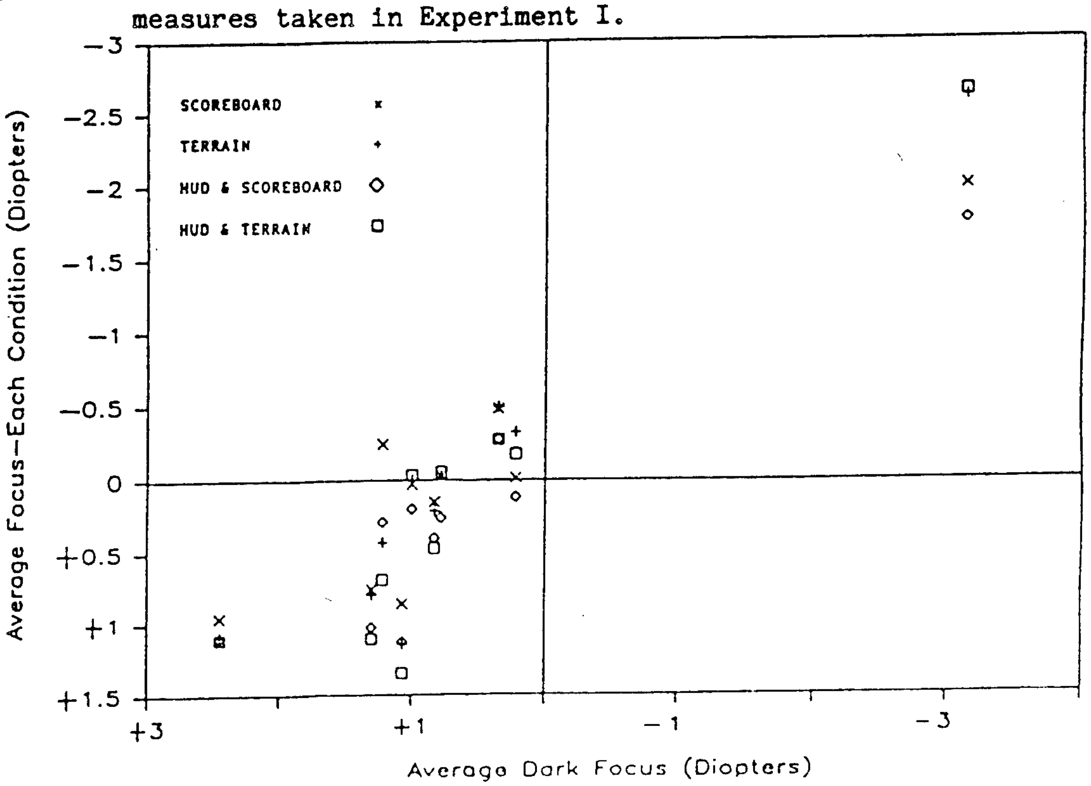


Figure 3. Correlation between average dark focus and all other focus measures taken in Experiment II.

Figure 4 shows how the pull of the dark focus affected the responses of each subject when the HUD was on. The averages of the responses to the terrain only and to the terrain plus scoreboard with the HUD On and Off are plotted relative to each subject's dark focus. These values were obtained by averaging those for Conditions 8 and 11 (HUD Off) and 9 and 12 (HUD On), respectively, and subtracting the respective average dark focus values. Figure 3 shows that, when the HUD is used, focus consistently shifts inward toward the dark foci of all 9 subjects with positive resting values (but away from the extremely distant dark focus of Subject 9). The amount of shift is a varying compromise between the pull of the scoreboard and/or terrain and the pull of the dark focus.

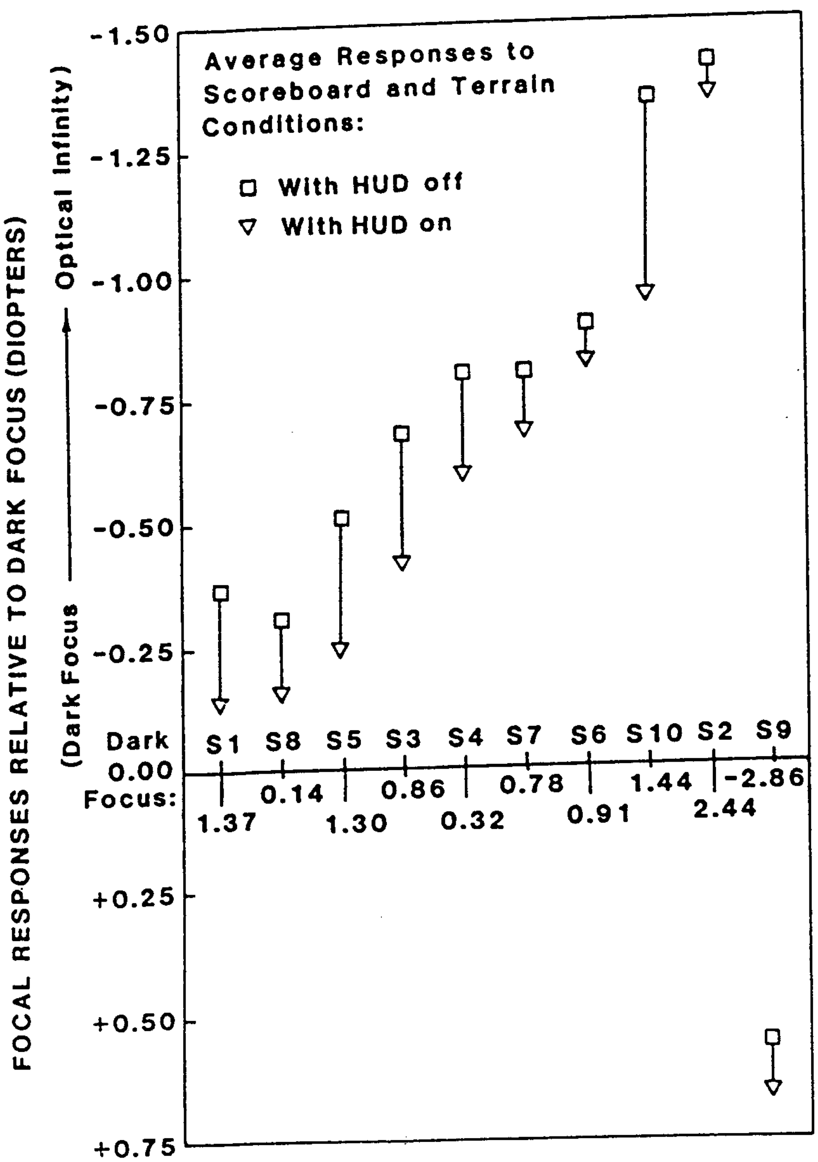


Figure 4. Average focal responses to the scoreboard and terrain conditions with the HUD On and Off, plotted relative to each individual's dark focus.

The HUD acted as an intervening stimulus allowing the eyes to lapse back toward their resting state. Simultaneous use of the HUD and terrain actually created a situation in which neither was in best focus. Focus was a compromise between the weak drawing power of the HUD stimulus and the strong pull of the scoreboard target. The negative effects of a compromise focus distance can be expected to fall more heavily on the terrain targets. HUD symbols are typically bold and large. Being somewhat out of focus would not make them difficult to read. However, the ability to resolve small, difficult-to-see targets in the terrain can be expected to be significantly degraded by being out of focus whenever the HUD is used.

Table 6 summarizes the average focus in diopters and in meters for each condition. The dark focus, HUD in dark, cloud, and HUD in cloud all caused focus to lie between 1.5 to 2.0 meters on average. As soon as distant terrain became visible, even with no visual task involved, the eyes were drawn outward to 33 meters on average. But, when the HUD was superposed on that terrain, focus lapsed back to a compromise distance of 6 meters, not quite as inward as the dark focus. Furthermore, if the terrain contained distant targets and the HUD were off, focus was pulled outward by varying amounts that averaged 0 D for the group. Again, as soon as the HUD was turned on and simultaneously used, focus lapsed inward to a 4-meter compromise.

TABLE 6

Mean Values of Eye Focus in Diopters for the Various Conditions in Experiments I and II with Composite Values for Both Experiments Given in Diopters and in Meters

Condition	Experiment I	Experiment II	Composite	
	(D)	(D)	(D)	(1/D = Meters)
Dark Focus	0.73	0.61	0.67	1.49
HUD in Dark	0.49		0.49	2.04
Cloud	0.66		0.66	1.52
HUD + Cloud	0.56		0.56	1.79
Terrain	-0.01	0.06	0.03	33.33
HUD + Terrain	0.10	0.21	0.16	6.25
Scoreboard		0.00	0.00	inf.
HUD + Scoreboard		0.25	0.25	4.00

These real-distance-of-focus results are also graphically depicted in Figure 5. The bar graph noticeably indicates that all HUD conditions, whether terrain targets are simultaneously used or not, allow focus to remain close to, and in some cases actually at, the resting distance. On the other hand, viewing distant terrain without a HUD greatly increases the distance of focus, the farthest focus occurring when the terrain contains small targets that must be seen and recognized.

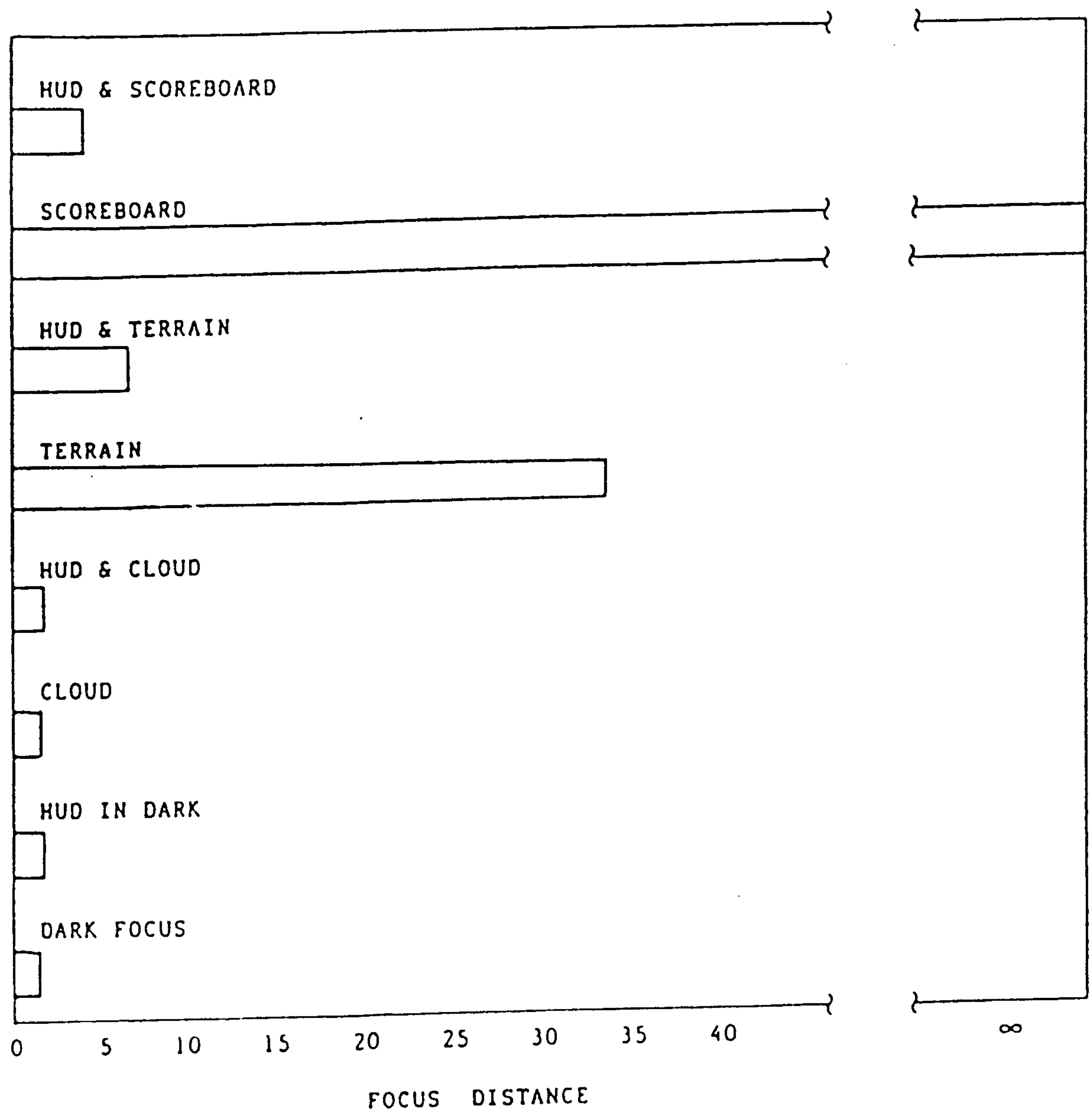


Figure 5. Distance of focus in meters for conditions measured in Experiments I and II combined.

DISCUSSION

The two experiments reported herein demonstrate that where the eye focuses for <u>any</u> stimulus is greatly dependent on an individual's own dark focus. The eye tends to focus within a range around the dark focus distance, which appears to act as the starting point. Simply knowing an individual's dark focus accounted for 88% of the variability in focus over all the experimental conditions. How far the eye moves away from the dark focus is determined by:

- the ambient conditions
- the acuity demands of the visual task, and
- the existence and nature of a textural gradient extending either toward or beyond an object to be resolved.

However, there are some people who will never actually focus at optical infinity, no matter how demanding the acuity task or how distant the gradient. This is particularily true for people whose dark focus is relatively close (like Subjects 1, 2, and 5) or very far (like Subject 9). Only people with a dark focus close to optical infinity tend to stay there. Thus, because most people have a dark focus that is closer than optical infinity, looking at and trying to resolve collimated targets will not result in infinity focus for many people with normal visual acuity.

Specific examples of how the eye fails to respond to a head-up display as generally assumed are the following:

1. When the HUD is used, it produces focusing shifts toward the dark focus, which varies from individual to individual.

2. Focus while simultaneously viewing the HUD and a distant real-world target differs from the response to the distant real-world target alone.

3. Collimated virtual targets induce a smaller shift from the dark focus than real targets at optical infinity.

4. Focus to the HUD used in clouds is generally closer to the individual's dark focus than is focus to the HUD against a distant real-world texture gradient; in fact, there was not a significant difference between responses to the HUD-plus-cloud condition and the individual dark foci.

Focal distance shifted between using distant real-world terrain and using HUD symbols, causing both to be slightly out of focus. In every condition, the measured focus responses seemed to be a compromise between the pull of the dark focus and the pull of the visual task at hand. When the terrain contained a demanding acuity task, namely the scoreboard, the pull was greatest away from the dark focus. When the terrain contained no task, the pull from the dark focus was also large, although a little less distant than when acuity demand was present. However, whenever the HUD was used, whether

alone or simultaneously with terrain targets, the eyes lapsed significantly toward their dark focus.

These lapses toward the dark focus caused by the HUD can produce dangerous misperceptions by a pilot of his position in space. The relationship between accommodation shifts and changes in apparent size and distance of objects is now well established (Hull, Gill, and Roscoe, 1982; Iavecchia, Iavecchia, and Roscoe, 1983; Randle, Roscoe, and Petitt, 1980; Roscoe, 1984, 1985). When focus shifts inward, the apparent visual angle subtended by distant surface objects, such as an airport runway or a military target, shrinks, thereby causing it to appear smaller and farther away than it actually is.

Surface objects not only appear smaller and farther away, causing pilots to overshoot on landing approaches, but the surface itself appears higher in the visual field, causing pilots to round out high and land hard. This effect has been demonstrated in flight simulators with visual systems (Palmer and Cronn, 1973; Randle, Roscoe, and Petitt, 1980) and in airplanes with flight periscopes (Campbell, McEachern, and Marg, 1955; Roscoe, 1950, 1984, 1985; Roscoe, Hasler, and Dougherty, 1966), both of which cause most pilots' eyes to focus too near, as does the HUD.

Eventually the pilot will suddenly realize that he is overshooting, but by the time the misjudgment becomes apparent, the combined response capabilities of the pilot and the airplane may be too slow to recover and avert the mishap. In these cases, the pilot error is a misjudgment resulting from systematic misaccommodation. Results of the present study clearly show that the HUD causes misaccommodation relative to the terrain by releasing the eyes' focus to lapse toward its resting state.

Erroneous judgments of the aircraft's position in space relative to the terrain or objects in it can be expected, and these misjudgments can have disastrous effects, especially in low-level attacks. Moreover, flying the HUD in solid IMC will allow the pilot's eyes to lapse all the way to their resting state. The pilot's eyes will not be prepared to see the terrain clearly and accurately localize surface objects, distant air threats, or other friendly aircraft.

When flying in and out of clouds in scattered or broken IMC conditions, the HUD will cause the pilot's eyes to be continually shifting focus between the dark focus in the cloud and the outward pull of the terrain when breaking out. These shifts can be expected to be minimized for pilots with a dark focus close to infinity. For all others, the amount of the shift will increase as well as the amount of misperceptions of apparent size and distance of objects and their angular position in apparent visual space.

The inability of the HUD to act as a sufficient distant-focus stimulus may be partly due to the size of typical HUD symbology. HUD symbols have been designed to be bold and very easily resolvable. This reduces the acuity demand of the symbols. The eyes are then permitted to lapse toward the dark focus while still maintaining sufficient clarity for symbols to be legible. It is even possible that bold symbols are detrimental in this respect and that increasing the acuity demand of HUD symbols might be beneficial. This

is not to say that the size effect is the only one causing the inward pull of the HUD, but it could be a contributor.

Because of the huge individual differences in dark foci and focus responses to stimuli, any particular optical correction on the HUD will not be appropriate for everyone, nor will any single value be optimum for flying at high altitude or in IMC in an empty-field condition and also at low levels as in terrain following or target acquisition and bombing. However, Owens and Leibowitz (1976) have shown that an optical correction equal to half the difference between a person's dark focus and optical infinity is best for night driving. In further support of this observation, Norman and Ehrlich (1985) recently found that a group of Israeli pilots, on average, focused near optical infinity only when a negative focus demand of 0.5 D was applied. Although it is not known exactly how the optimum focus correction changes when the nature of the acuity task or the visible scene changes, the required adjustment for different individuals may be on the order of the value reported by Owens and Leibowitz.

Until HUDs are manufactured with redesigned optics, accommodation training for pilots flying HUD-equipped aircraft is a possible quick fix. A biofeedback technique developed by Randle (1970) uses auditory feedback of the accommodative state. The pitch of an audible tone is modulated by the output signal from a covert infrared tracking optometer. As the observer learns the relationship between pitch and accommodation, accommodation can be gradually brought under voluntary control. The limitation to this quick fix is that it may fail during stress situations and it will not take away the fact that the HUD creates a constant tendency toward misaccommodation.

In view of the serious operational concerns about pilot disorientation and misorientation since virtual imaging displays have come into wide use, some corrective action is necessary. To minimize the misjudment problems associated with virtual imaging displays and to improve their safety and operational effectiveness, adjustable optical refraction appears to be required, just as people who wear glasses require different amounts of correction. If a manual adjustment for differences among pilots' eyes is provided, inserting further minor corrections for specific task conditions would also be possible.

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